Draft Final Report

Analysis of Traffic Delays from Flooding

Des Plaines River Watershed Study

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to

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and

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Table of Contents

1. Introduction

The Chicago District of the U.S. Army Corps of Engineers, in collaboration with the Illinois Department of Natural Resources, the Illinois Department of Transportation, the Lake County Division of Transportation and the Cook County Highway Department, intend to assess the delays to road traffic resulting from flooding of the Des Plaines River and its tributaries in Lake and Cook Counties, Illinois. The estimates relate to:

1. delays resulting from flooded roads;

2. delays due to flooded road repairs;

3. delays due to recommended plan project construction.

Traffic delays are needed for a base year and several future years for floods of varying depths and duration. The usual flood frequency profile analyzed includes 2, 5, 10, 25, 50, 100 and 500-year frequency floods.

The Transportation Laboratory of the Department of Civil and Materials Engineering, University of Illinois at Chicago, has conducted a prototype analysis of traffic delays from flooding of the main stem of the Des Plaines River, building on forecasts of current and future traffic made by the Chicago Area Transportation Study (CATS), the Federally designated metropolitan transportation planning organization for the six-county Northeastern Illinois region.

This Final Report documents the findings of a 15-month study initiated in June 2001. The report is intended to be a brief, non-technical explanation of the method applied, the computational experiments conducted and the findings of those experiments. It is not intended to be a guide on how to perform such an analysis or a thorough documentation of the data used. Replication of the analysis, however, should be straightforward for analysts familiar with the Traffic Assignment method applied in this study and the data files provided by CATS.

The report is organized in the following way. First in Section 2, the problem to be analyzed is stated, the general approach to the analysis is described together with the data employed. Then in Section 3, the Traffic Assignment method employed in the analysis is described, together with its assumptions. This description is intended to allow persons unfamiliar with the method to understand the basic concept and its limitations. In Section 4, the findings of the application of the method are presented in two parts. First, estimates of additional travel times and distances from flood events are summarized; detailed tables are found in the Appendix. Second, the effects of floodproofing an individual river crossing with regard to a specified flood event are analyzed for 100-year and 5-year flood events. Finally, the combined effect of floodproofing two or three river crossings is examined. Recommendations for application of the method are presented in Section 5. All tables and figures are placed following the References.

2. Problem and Approach

2.1 Problem Statement

The flooding of the Des Plaines River and similar smaller rivers temporarily disrupts road traffic through the closing of bridges and associated roadways. Such flood events may persist for a few hours up to a few days, depending on the severity of the storm causing the event.

The direct impact of such road closings is that drivers must find other routes of travel, which may lead temporarily to highly congested conditions, depending on the extent of the flooding. The drivers affected include cars, trucks of various sizes, and buses. In the case of cars, the indirect effects of road closings are that travelers may choose a different mode, such as public transit, or to a different destination, or decide to travel at a different time or cancel the trip altogether. In this study, the analysis of the effects of road closings is restricted to changes of route only. Extension of this approach to include changes of mode and destination are relatively straightforward, given recent developments and implementations of models that combine route, mode and destination choices into a single model (Boyce and Bar-Gera, 2003). Extension of the model to include travel at a different time of day, or cancellation of the trip, however, has generally not been attempted in models of this type.

2.2 Approach

The approach implemented in this study of re-routings, and the estimation of associated traffic delays, is to apply a Traffic Assignment method (also known as a route choice model) to estimate road traffic delays and added travel distances from bridge closings. The approach was investigated through its use on closings of river crossings on the main stem of the Des Plaines River identified during an earlier study, known as the 1999 Feasibility Study.

The procedure for applying the Traffic Assignment method is the following.

1. Road segments subject to delays from flooding in the main stem of the Des Plaines River Watershed were identified in the CATS road network, shown as Figure 1;

2. Additional arterial and collector road segments within the Watershed not represented in the CATS road network were examined to determine if they were critical to the analysis; none were identified, since CATS road network is very detailed in the area of the study;

3. The zone system within and around the Des Plaines Watershed was examined to determine whether it is sufficiently detailed for the intended analysis; for the analysis reported here, it was not necessary to divide zones to provide for more detail;

4. CATS estimates of zone-to-zone automobile travel for five classes of person trips and four time periods during the 24-hour weekday in 1996 and 2020 were factored from the results of analyses performed by CATS for air quality conformity modeling. The factoring procedure is relatively complex, but follows procedures described in CATS (1997). The trips classes are the following:

a. home to work
b. home to non-work
c. nonhome to all destinations
d. trips with origins or destinations outside the region (external trips)
e. trips to and from the region's airports

In addition, trips made by four classes of trucks (B-plate, light, medium and heavy) were factored by time of day. B-plate is the designation for pick-up trucks and commercial vans. In the traffic assignments, trucks are converted to auto equivalents with weights of one, one, two and three, respectively.

The four time periods are defined as follows:

a. 6 – 9 am
b. 9 am – 4 pm
c. 4 – 6 pm
d. 6 pm – 6 am

For time periods a-c, travel is assumed to be evenly distributed over the time period, and the total travel time and distances are obtained by multiplying the hourly travel estimates by the number of hours. In the fourth time period, however, travel is assumed to be largely concentrated in five hours of the 12-hour period. Accordingly, the hourly travel times and distances are estimated for hourly flows equal to one-fifth of the total, and the total time and distances obtained by multiplying the hourly estimate by 5. These were aggregated into the three periods shown above. The zone system and the districts defined on these zones are shown as Figure 2.

5. The Traffic Assignment method was applied to flood scenarios involving the main stem of the Des Plaines River only for the following floods: 5, 10, 25, 50, 100, and 500 year frequencies, plus the normal or base condition, for the morning peak period (6-9 am), and for all four time periods for the 25 and 100 year flood events. The 2-year flood event was also considered; since only one minor river crossing on the main stem is disrupted by such an event, the delays from a 2-year event are not distinguishable from normal conditions. From the results for the 25 and 100-year flood events, it was observed that the daily travel times and distances were proportional to the 6-9 am hourly travel times and distances. For this reason, the four-period analysis was deemed to be unnecessary for the other four flood events. Total travel times and travel distances corresponding to these flood scenarios were identified, first on a zone-to-zone basis for the 1790 zones in the Chicago region, and then on an aggregated district-to-district basis.

6. Results of the analysis were summarized in tables, and examples plotted in charts for use by the Chicago District to demonstrate the results from the application of the method. Results reported here are total and mean vehicle travel time, and total and mean vehicle travel distance, between 21 districts comprising the larger Chicago metropolitan region.

3. Brief Explanation of the Traffic Assignment Method

Given an estimate of the total flow of vehicles per hour from origin zone to destination zone, the Traffic Assignment method seeks to allocate these flows to one or more routes through the road network in order that *the travel time on the used routes between each origin-destination* (OD) *pair are equal, and no more than the travel times on unused routes.* In other words, the model assumes that each driver seeks to find her/his shortest route through the network in terms of travel time.

The travel time of each link and route in the network depends on the flows between all zones in the region, and not just the zone pair of interest. The link travel times are generally assumed to be a deterministic, increasing function of link flow, in which the travel time increases without limit as the flow increases without limit. This assumption may be questioned since it does not recognize that link flows can only increase to a maximum flow, known as link capacity, and once capacity is reached may actually decrease to a lower flow with substantially higher travel times. The standard traffic assignment method, to the contrary, assumes that travel times increase with increasing flow. The assumption is a practical one designed to render the solution of the optimization problem manageable, and its solution unique. The resulting time-flow function may be regarded as a reasonable approximation of reality within the range of actual flows.

To determine the link flows, a large-scale optimization problem is solved for a road network and zone system; a statement of this optimization problem is given in Appendix A-1. A property of the solution to the problem is that the flows on each link of the network in the optimal solution are unique. However, the route flows are not unique, since route flows could be re-routed in many ways leaving the link flows unchanged. Therefore, one cannot draw conclusions about which particular zone-to-zone flows are affected by any river crossing being closed.

The method also implicitly assumes that drivers know their best routes precisely, even though the flooded network may be different from the one they normally use. Since this assumption may be somewhat unrealistic in a flooded condition, the results of the analysis may be considered to be a lower bound on the actual delays. Since some trips may not be made during a flood event, reducing the amount of travel overall, the use of this lower bound to approximate the overall effect of the flood seems reasonable. Moreover, for the purposes of scenario analyses, the results are fully consistent and therefore comparable.

A final assumption of the analysis is that all zone-to-zone flows do arrive at their destinations, although the travel times may be rather high. In other words, links do not become fully blocked by traffic. This phenomenon is a result of the simpler, steady state form of this static route choice model, as compared with a more precise, and much more computationally difficult, dynamic route choice model.

In summary, then, the standard Traffic Assignment method, or route choice model, is a static and deterministic formulation. As such, it is a substantial simplification of reality, but one that is solvable for large-scale networks, such as the 40,000 directional-link road network representation of CATS. Two alternative models could be considered to this method. One class of models relaxes the assumption of perfect information about the state of the road network.

However, solvable models relax this assumption in a rather simplistic manner by assuming a random perception error is associated with the travel time of each route, leading to the so-called logit route choice model. One shortcoming of this model is that each feasible route between each OD pair is allocated some flow, no matter how circuitous is the route. Furthermore, there is little empirical justification for the use of the logit choice function, its tractability being the main reason for its popularity. The perception errors embodied in this model have nothing to do with flooded river crossings.

A second class of models mentioned above pertains to dynamic models, in which flows are associated with short intervals of time of perhaps one to five minutes. In such models the delays associated with river crossings might be represented by a queuing relationship, and delays associated with unexpected bridge closings considered. Such models remain in an early stage of operational development for large-scale road networks. An example of the application of a dynamic model to the Chicago road network is the VISTA model of Ziliaskopoulos (for a review of this and other dynamic models, see Peeta and Ziliaskopoulos, 2001). Presently, the solution of this model for the Chicago region requires several days of computational effort, as contrasted with a few hours for the much simpler static model employed in this project. Another possible shortcoming of the model is that few time-dependent data on departure rates are available.

4. Findings of the Analysis

In this section, two sets of findings are presented. The first set concern estimates and forecasts of increased travel times and distances from flood events on the main stem of the Des Plaines River. The second set pertains to investigations of the reduction of travel times and distances resulting from improvements to maintain traffic on river crossings during flood events.

4.1 Findings Related to Increased Travel Times and Distances from Flood Events

Links in the CATS road network that were identified as being affected by flood events of various frequencies are shown in Table A-1, Appendix, and summarized in Table 1. Altogether 196 one-way links totaling 235.4 miles in length were identified based on tables furnished by the Chicago District. The flood frequencies range from the 5-year flood to the 500-year flood. The 2-year flood was not analyzed because only one minor bridge was affected.

In many cases the links affected consist only of the pair that includes the Des Plaines River crossing subject to closure by flooding. In other cases, several or many links are closed at a given river mile location. For example at River mile 73.74, only two one-way links are closed by the 5-year flood, but 12 links are closed by the 500-year event.

The total origin-destination travel flows during the four weekday travel periods, in vehicles per hour, for 1996 and 2020 are shown in Table 2. Detailed tables are provided in the Appendix in A-2. In those tables, the flows between the 1,790 zones were aggregated to 21 districts as follows:

1. four districts in the City of Chicago;
2. three districts in suburban Cook County;
3. six districts each consisting of one of the collar counties around Cook County, including Lake County, Indiana;
4. four districts consisting of aggregations of outlying counties.

Then, each of the four districts traversed by the Des Plaines River was divided into two districts, one to the west (w) of the River, and the other to the east (e). These districts are from north to south: Lake County, IL; North Cook; West Chicago; and West Cook. These districts were formed so that the effect of bridge closings on areas traversed by the river could be directly identified. Figure 2 above also shows the location of these districts.

Table 3 shows the total travel time in hours and the total travel distance in miles for the normal or base no-flood condition and the six flood events in 1996. The columns labeled 6 – 9 am give the total travel times and distances for this morning peak period. The columns labeled 24 hours show the total daily travel times and distances. Note that the travel times and distances increase with the severity of the flood events. Since the times and distances are for the entire Chicago metropolitan region, the increases resulting from flood events on the Des Plaines River are relatively small.

Tables A-3 and A-4 in the Appendix show the district-to-district hourly travel times and distances for the 5, 10, 25, 50, 100 and 500-year flood events. Inspection of these tables shows the effect of the various events on total travel times and distances overall and for various pairs of districts. The cell values show the time from the row district to the column district. Each row shows the travel times from the origin district to each of the destination districts. Similarly, each column shows the total travel times to that destination from each of the origin districts. The last column shows the total travel time from each origin district. Likewise, the last row shows the total travel time to each destination district.

By dividing the hourly travel time by the hourly flow, the mean travel time can be computed. Table 5-A shows the mean district-to-district travel times for all flood events during the 6-9 am period. Comparison of these tables reveals the effect of the various floods at the district-to-district level. Similarly, Table 5-A shows the district-to-district mean travel distances for all flood events during the 6-9 am period. Since bridge closings result in rerouting of traffic flows, these mean travel distances are longer than those experienced during normal conditions.

4.2 Findings Related to Reduced Travel Times and Distances from Floodproofing

The results reported in the above section show how the removal of river crossings from the road network affects travel times and distances. However, they do not show the relative benefits of floodproofing at a river crossing. The latter is the focus of this section.

4.2.1 100-Year Flood Event

In order to determine the relative importance of each crossing, the Traffic Assignment method was applied to the network available to traffic at a given flood event plus the addition of one of the crossings closed by that event. In the case of the 100-year flood event, 27 river crossings are closed. Therefore, all 27 crossings were removed from the road network, and each one in turn was replaced in the network. The resulting traffic assignment, compared with the assignment for the 100-year event, shows the relative importance of that crossing, in terms of travel time and distance saved. The results of this analysis for the 100-year event and its 27 crossings are shown in Table 5 and Figures 3 and 4.

In Table 5, the 27 crossings are ranked in the order of the travel time savings from floodproofing each crossing for the 100-year flood event. The savings are reported in this table as vehicle-hours of travel time for auto equivalents per clock hour during the morning peak period from 6-9 am. Obviously, the analysis could be extended to the entire day, but the savings would be proportional to the amounts shown, so the ranking would be unchanged. Detailed effects of trucks could also be added. The maximum savings shown for the 100-year event is 5,638 vehicle-hours per clock-hour for the entire Chicago region for floodproofing the crossing at Dundee Road in northern Cook County.

The travel distances from replacing each crossing were also computed from the same traffic assignment, and the savings in vehicle-miles of travel determined. The maximum savings in vehicle-miles of travel is 101,734 vehicle-miles per hour, also for Dundee Road. The rank order of the travel distance savings is similar, but not always the same as the travel time savings.

The travel time and distance savings can be visualized better by plotting the values for each crossing versus its river milepost, as shown in Figures 3 and 4. The river crossing mileposts closed in the 100-year event range from 49.00 at Roosevelt Road to 110.04 at Kilbourne Road in northern Lake County, Illinois. Since Roosevelt Road and I-290 are near the south end of the main stem, traffic is not substantially affected by their closing, since alternative routes to the south and north are available. The most affected crossings are Dundee Road and Lake-Cook Roads, at the midpoint of the main stem considered in this example. In the figures, some of the points are labeled to facilitate their identification. Other points can be readily identified by referring to Table 5.

The travel time versus travel distance savings are plotted in Figure 5. This figure clearly shows that Dundee and Lake-Cook Roads achieve the highest savings when considered independently. Next in importance are Palatine, Townline and Deerfield Roads. Since Dundee, Lake-Cook and Palatine Roads are adjacent to each other, they may be regarded as rough substitutes. Therefore, the next step is to consider combinations of river crossing floodproofing that reduce the total time and distance to a maximum extent. To this end, traffic assignments were performed for the three leading crossings, Dundee, Lake-Cook and Palatine Roads, together with one or two more crossings.

Through trial-and-error experimentation, it was found that crossings at substantially different locations from this area in northern Cook County achieved the largest additional reduction in travel time and distance. Table 6 and Figure 6 shows these results. In Table 6, one and two additional river crossings are replaced in the network. The total savings in travel time and distance are shown for each combination. The largest savings from floodproofing two crossings is Dundee Road plus Belvidere Road in northern Lake County. By adding I-290 in western Cook County to this combination, the largest savings from three crossings is found. As noted, these combinations were determined on a trail-and-error basis. There could be other combinations of two and three crossings with somewhat higher savings.

4.2.2 5-Year Flood Event

The same analysis was performed for the 5-year flood event. In this smaller event, only seven road segments are affected, but three are north-south segments paralleling the River, as shown in Table 7. Hence, the effect of this flood event is smaller and directionally different than the 100-year event. Floodproofing of Des Plaines River Road in northern Cook County has the largest savings in travel time and distance, but it is small compared to crossings in the 100-year event.

Figures 7 and 8 show the travel time and distances savings over the 5-year event by river milepost. For the north-south road segments, the milepost refers to a nominal location representing the entire segment. Figure 9 shows the travel time savings vs. the travel distance savings. Combinations of river crossings are examined in Table 8 and Figure 10. Two north-south road segments, Des Plaines River Road and First Avenue, dominate all other combinations.

4.3 Systematic Search for Combinations of River Crossings

As noted above, the combinations of river crossings found to reduce travel time and distance most effectively were found on a trial-and-error basis. However, an effort was undertaken to identify simple indicators of which crossings were likely to be most effective in reducing travel time and distance. These results are summarized in this subsection.

First, the effect of crossings considered individually were determined, as shown in Tables 5 and 7. Then, the most effective single crossing was combined with each of the other high ranking crossings. It was observed that crossings in the same vicinity, which act as substitutes, were ineffective in reducing time and distance further. Instead, crossings at substantially different locations were observed to be more effective. Accordingly, crossings in northern Cook County were most effective when combined with crossings further north in Lake County, or further south in western Cook County.

Other indicators were examined such as link capacity, link volume and volume-to-capacity ratio. None was found to be effective in predicting effective combinations of crossings. Origin-destination flows in the general vicinity of the crossing were also considered; likewise, these flows were not found to be a useful predictor. Therefore, we are left with the separation rule as the only effective predictor.

5. Recommendations

The experience of the authors in working with the prototype method described in Section 3, the findings reported in Section 4, and the reactions of the Transportation Subcommittee to date, suggest that this approach is suitable for application in the Des Plaines Phase 2 Study.

Some extensions of the method are likely to be necessary during its application in Phase 2 in view of the more rural character of parts of the Des Plaines River Watershed. The following recommendations represent the authors understanding of the additional work elements that will be required in the Phase 2 study:

1. Review the travel estimates and forecasts within the Des Plaines River Watershed to determine whether there is sufficient detail in the CATS zone system, especially in Lake County, Illinois, where zones of four square miles are prevalent.

2. Determine in consultation with the Study Committee whether an expansion of the traffic analysis into Kenosha County is needed; if such an expansion is required, road networks, zone systems and demand forecasts will need to be obtained from the Southeastern Wisconsin Regional Planning Commission, in cooperation with Kenosha County transportation staff.

3. Disaggregate the base and future year travel forecasts so as to provide the additional detail needed for flood analysis within the Des Plaines River Watershed.

4. Determine whether the representation of the road network is sufficiently detailed to permit analysis of potentially required road segments within the Watershed; in particular, examine whether road segments within the Watershed in Lake and Kenosha Counties are adequately represented.

5. Code the necessary additional road segments into the network.

6. As candidates for analysis are identified, initiate the travel time and distance analysis applied in this prototype study for the several flood events requiring analysis.

Presently, the latest travel forecasts available from CATS are for 2020, as well as certain intermediate years. CATS is presently updating the Regional Transportation Plan to 2030. When this plan update is completed, travel forecasts will be available for 2030 as well.

The studies conducted in this project were performed with the EMME/2 transportation planning software system, which is compatible with the system utilized by CATS. Application of the method described in this report will require a software license for EMME/2 or a comparable software system. Additional information regarding the EMME/2 system can be found at http://www.inro.ca. Information on one comparable software system, TransCAD, may be found at http://www.caliper.com. Application of either system requires personnel trained in the use of the software system.

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List of Tables

Table 1. Links of the Chicago Region Road Network Closed by Flood Events

Flood Event:	5 year	10 year	25 year	50 year	100 year	500 year
Total Number of Links Closed:	74	90	116	150	174	196
Length of Closed Links (miles):	82.3	104.9	136.3	178.4	210.1	235.4

Number of Links in the Chicago Region Road Network - 39,282 links
Total Link Length in the Chicago Region Road Network - 34,690 miles

Table 2. Total Vehicle Flow by Period and Year (vehicles/hour)

year:	1996			2020		
period	autos	trucks	auto equiv.	autos	trucks	auto equiv.
6 - 9 am	933,030	264,807	1,097,836	1,359,889	255,916	1,615,790
9 am - 4 pm	966,949	190,644	1,157,589	1,517,688	305,268	1,822,967
4 - 6 pm	1,377,569	80,923	1,458,489	2,097,519	130,610	4,438,262
6 pm - 6 am	806,084	23,548	829,633	1,239,003	37,696	1,276,618
Note: trucks are weighted by type.						

Table 3. Travel Times and Distances for Flood Events in 1996

Flood Event	Total Travel Time (hours)		Total Travel Distance (miles)	
	6 -9 am	24 hours	6 -9 am	24 hours
Normal	1,166,164	5,306,048	39,154,509	187,158,553
Five Year	1,173,344	5,338,716	39,185,133	187,304,936
Ten Year	1,177,080	5,355,714	39,265,050	187,686,939
Twenty-five Year	1,190,341	5,416,053	39,405,276	188,357,219
Fifty Year	1,215,867	5,532,193	39,723,327	189,877,503
Hundred Year	1,228,886	5,591,429	39,898,425	190,714,472
Five-hundred Year	1,249,323	5,684,420	40,101,060	191,683,067

Table 4. Travel Times and Distances for Flood Events in 2020

Flood Event	Total Travel Time (hours)		Total Travel Distance (miles)	
	6 -9 am	24 hours	6 -9 am	24 hours
Normal	1,614,612	7,346,483	50,078,217	239,373,877
Five Year	1,636,036	7,443,963	50,140,875	239,673,383
Ten Year	1,643,853	7,479,529	50,268,048	240,281,269
Twenty-five Year	1,659,619	7,551,266	50,400,534	240,914,553
Fifty Year	1,707,728	7,770,160	50,698,584	242,339,232
Hundred Year	1,729,213	7,867,917	50,903,670	243,319,543
Five-hundred Year	1,791,725	8,152,347	51,363,996	245,519,901

Table 5. Morning Peak Hour Travel Time and Distance Savings from Floodproofing Relative to the 100-Year Flood Event

Rank (time)	Milepost	River Crossing Floodproofed	Direction	Flood Event	Travel Time (vehicle-hours)	Reduction from 100-year	Travel Distance (vehicle-miles)	Reduction from 100-year
1	74.34	Dundee Road	EW	50	401,158	5,638	13,150,712	101,734
2	75.51	Lake-Cook Road	EW	25	401,200	5,596	13,152,344	100,102
3	71.72	Palatine Road	EW	25	402,824	3,972	13,184,583	67,863
4	83.66	Townline Road (IL 60)	EW	25	403,099	3,697	13,201,202	51,244
5	66.91	Golf Road	EW	5	403,346	3,450	13,204,821	47,625
6	65.39	Rand Road	EW	25	403,529	3,267	13,207,464	44,982
7	94.50	Belvidere Road	EW	5	403,556	3,240	13,215,194	37,252
8	91.10	Buckley Road (IL 137)	EW	25	403,571	3,225	13,224,726	27,720
9	76.76	Deerfield Road	EW	25	403,758	3,038	13,186,981	65,465
10	80.21	Half Day Road (IL 22)	EW	10	404,143	2,653	13,194,818	57,628
11	49.61	Eisenhower Expy (I-290)	EW	50	404,275	2,521	13,249,299	3,147
12	71.15	Des Plaines River Road	NS	5	404,355	2,441	13,239,152	13,294
13	97.12	Grand Avenue (IL 132)	EW	10	404,365	2,430	13,215,581	36,865
14	95.97	Washington Street	EW	10	404,574	2,222	13,217,197	35,249
15	68.00	Central Road	EW	100	404,919	1,877	13,225,672	26,774
16	99.92	US 41	NS	5	404,956	1,840	13,226,596	25,850
17	64.22	Algonquin Road	EW	25	405,577	1,219	13,238,408	14,038
18	87.81	Park Avenue (IL 176)	EW	5	405,707	1,089	13,238,985	13,461
19	51.62	First Avenue	NS	25	406,174	622	13,247,138	5,308
20	77.97	Milwaukee Avenue	NS	100	406,498	298	13,246,113	6,333
21	60.00	Higgins Road	EW	25	406,534	262	13,250,827	1,619
22	49.00	Roosvelt Road	EW	10	406,538	257	13,248,702	3,744
23	56.92	Irving Park Road	EW	100	406,554	242	13,250,459	1,987
24	51.62	Thatcher Road	EW	25	406,651	145	13,251,790	656
25	107.11	Rosecrans Road (IL 173)	EW	25	406,775	20	13,252,340	106
26	110.04	Kilbourne Road	EW	100	406,783	13	13,252,543	-
27	109.90	Russell Road	EW	10	406,799	-	13,252,351	95
100 Year Flood Event - all flooded links removed					406,796		13,252,446	
Normal Conditions - no links removed					385,769		13,007,305	

Table 6. Morning Peak Hour Travel Time and Distance Savings from Floodproofing Two or Three River Crossings Relative to the 100-Year Flood Event

Milepost	River Crossings Floodproofed	Travel Time (vehicle-hours)	Reduction from 100-year Event	Travel Distance (vehicle-miles)	Reduction from 100-year Event
74.34	Dundee Road	401,158	5,638	13,150,712	101,734
60.00	plus Higgins Road	400,938	5,858	13,149,457	102,989
71.15	plus Des Plaines River Road	399,108	7,688	13,144,276	108,170
75.51	plus Lake-Cook Road	399,052	7,744	13,131,582	120,864
94.50	plus Belvidere Road	398,595	8,201	13,122,039	130,407
49.61	and I-290	396,247	10,549	13,118,003	134,443
66.91	and Golf Road	396,426	10,370	13,096,909	155,537
75.51	Lake-Cook Road	401,200	5,596	13,152,344	100,102
51.62	plus First Avenue	400,583	6,213	13,146,953	105,493
91.10	plus Buckley Road	398,935	7,861	13,137,889	114,557
65.39	plus Rand Road	398,926	7,869	13,121,973	130,473
49.61	plus I-290	398,836	7,960	13,148,472	103,974
94.40	plus Belvidere Road	398,670	8,126	13,123,691	128,755
71.72	Palatine Road	402,824	3,972	13,184,583	67,863
94.50	plus Belvidere Road	399,991	6,805	13,152,762	99,684
66.91	plus Golf Road	400,377	6,419	13,155,280	97,166
49.61	and I-290	398,093	8,703	13,151,130	101,316
100-Year Flood Event - flooded links removed		406,796	-	13,252,446	-
Normal Conditions - no links removed		385,769	21,027	13,007,305	245,141

Table 7. Morning Peak Hour Travel Time and Distance Savings from Floodproofing Relative to the 5-Year Flood Event

Rank (time)	Milepost	River Crossing Floodproofed	Direction	Flood Event	Travel Time (vehicle-hours)	Reduction from 5-year	Travel Distance (vehicle-miles)	Reduction from 5-year
1	71.15	Des Plaines River Road	NS	5	386,517	1,853	13,015,133	5,202
2	51.62	First Avenue	NS	5	388,051	319	13,016,832	3,503
3	66.91	Golf Road	EW	5	388,221	149	13,019,464	871
4	94.50	Belvidere Road	EW	5	388,240	130	13,019,355	980
5	99.92	US 41	NS	5	388,284	86	13,019,599	736
6	51.62	Thatcher Road	EW	5	388,304	66	13,019,874	461
7	110.04	Kilbourne Road	EW	5	388,352	18	13,019,512	823
5-Year Flood Event - all flooded links removed					388,370		13,020,335	
Normal Conditions - no links removed					385,769		13,007,305	

Table 8. Morning Peak Hour Travel Time and Distance Savings from Floodproofing Two River Crossings Relative to the 5-Year Flood Event

Milepost	River Crossings Floodproofed	Travel Time (vehicle-hours)	Reduction from 5-year Event	Travel Distance (vehicle-miles)	Reduction from 5-year Event
71.15	Des Plaines River Road	386,517	1,853	13,015,133	5,202
51.62	plus First Avenue	386,201	2,169	13,011,629	8,706
66.91	plus Golf Road	386,380	1,990	13,013,670	6,665
94.50	plus Belvidere Road	386,389	1,981	13,013,967	6,368
99.92	plus US 41	386,426	1,944	13,014,339	5,996
51.62	plus Thatcher Road	386,455	1,915	13,014,672	5,663
110.04	plus Kilbourne Road	386,491	1,879	13,014,204	6,131
51.62	First Avenue	388,051	319	13,016,832	3,503
66.91	plus Golf Road	387,873	497	13,015,514	4,821
94.50	plus Belvidere Road	387,917	453	13,015,870	4,465
99.92	plus US 41	387,975	395	13,016,329	4,006
51.62	plus Thatcher Road	388,010	360	13,016,675	3,660
110.04	plus Kilbourne Road	388,041	329	13,015,837	4,498
66.91	Golf Road	388,221	149	13,019,464	871
94.50	plus Belvidere Road	388,069	301	13,018,091	2,244
99.92	plus US 41	388,101	269	13,018,374	1,961
51.62	plus Thatcher Road	388,144	226	13,018,770	1,565
110.04	plus Kilbourne Road	388,191	179	13,018,351	1,984
5-Year Flood Event - flooded links removed		388,370	-	13,020,335	-
Normal Conditions - no links removed		385,769	2,601	13,007,305	13,030

List of Figures

Figure 1. Chicago Region Road Network, 1996

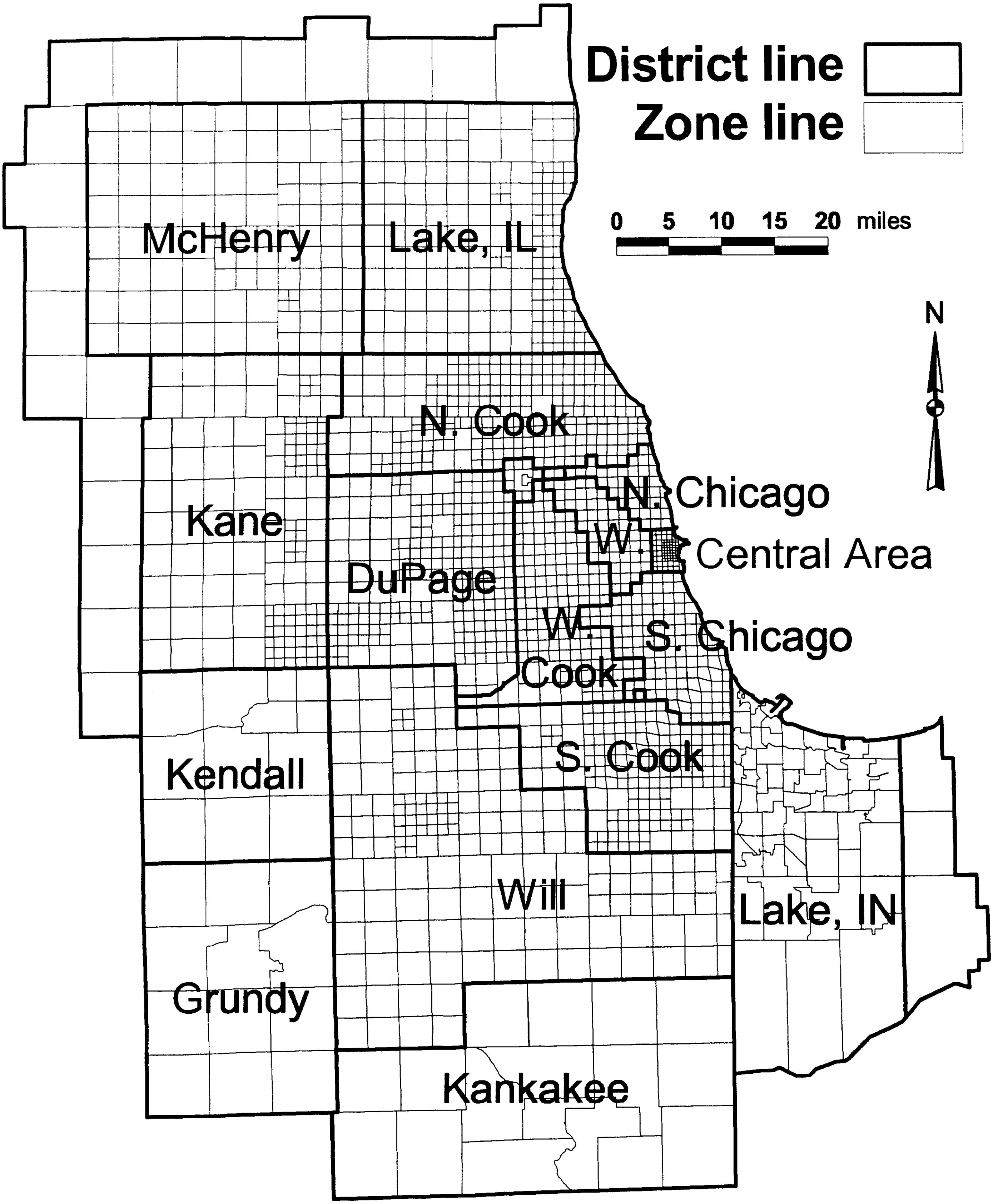


Figure 2. Chicago Region Zone System and Districts

Figure 3. Travel Time Savings from Flood Protection at Milepost N Relative to the 100-Year Flood Event
(6 - 9 am period in 2020)

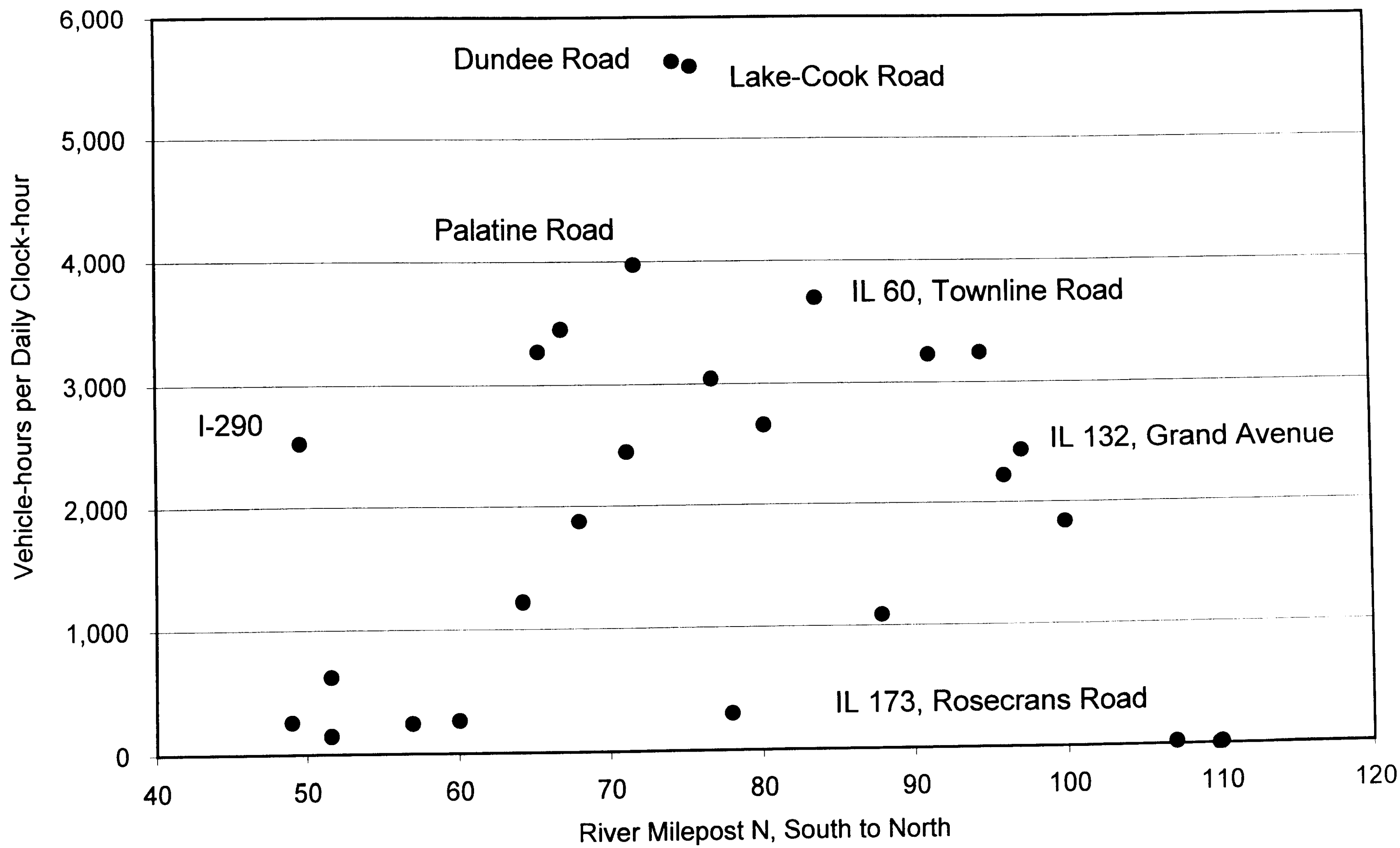


Figure 4. Travel Distance Savings from Flood Protection at Milepost N Relative to the 100-Year Flood Event
(6 - 9 am period in 2020)

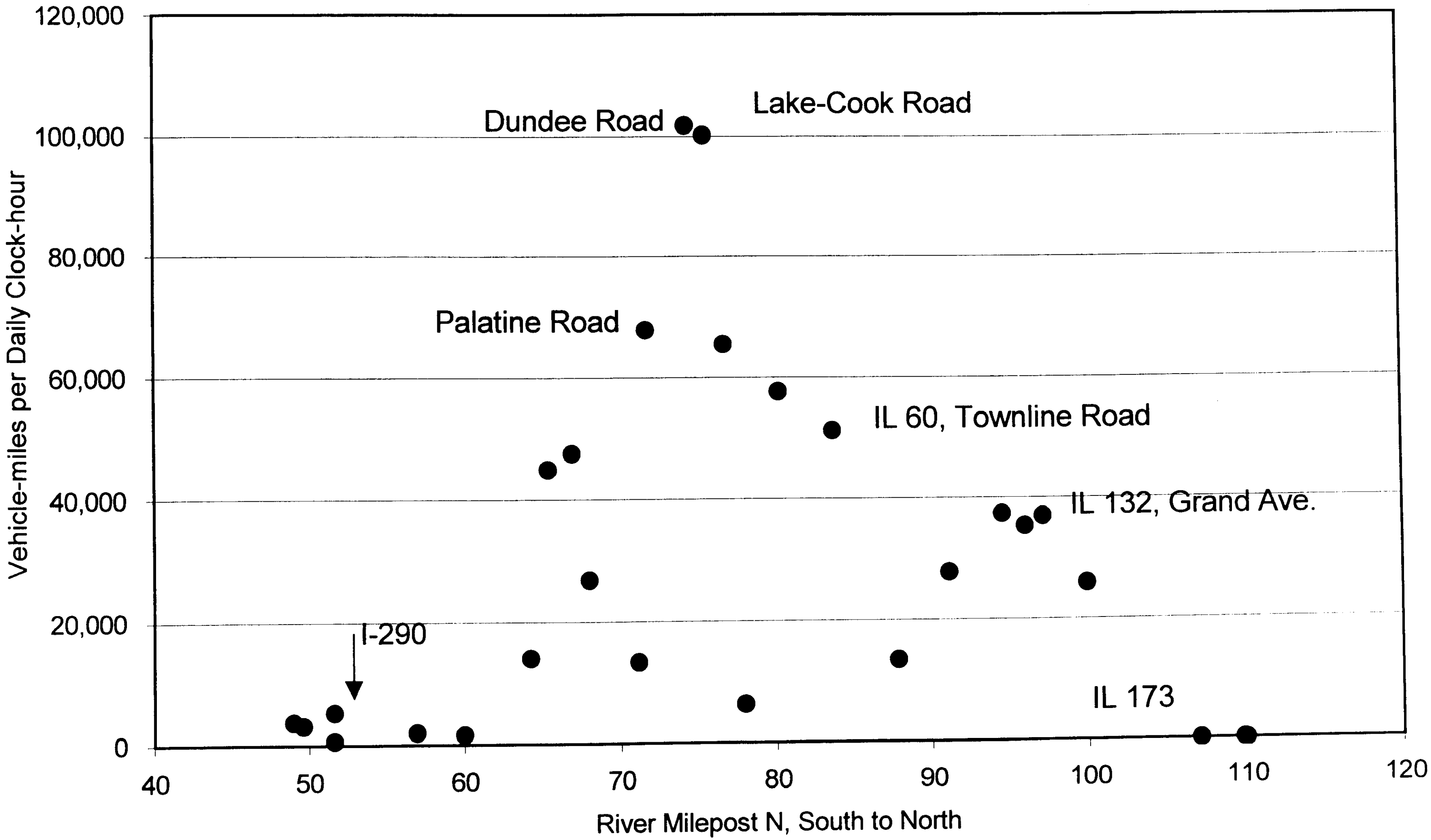


Figure 5. Travel Time vs. Distance Savings from Flood Protection at Each River Crossing for the 100-Year Flood Event
(6 - 9 am period in 2020)

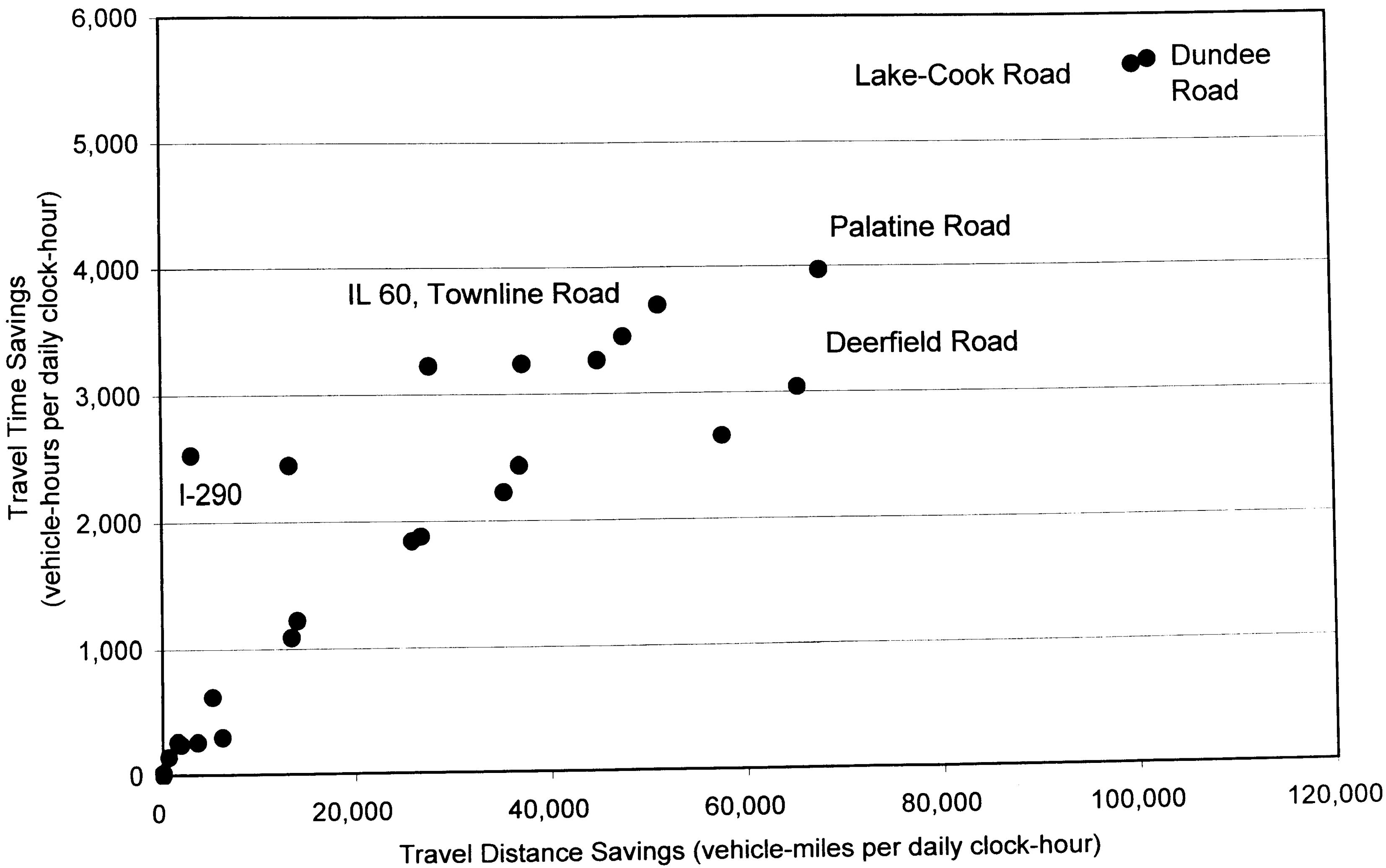


Figure 6. Travel Time vs. Distance Savings from Flood Protection for Combinations of Two and Three River Crossings for the 100-Year Flood Event
(6 - 9 am period in 2020)

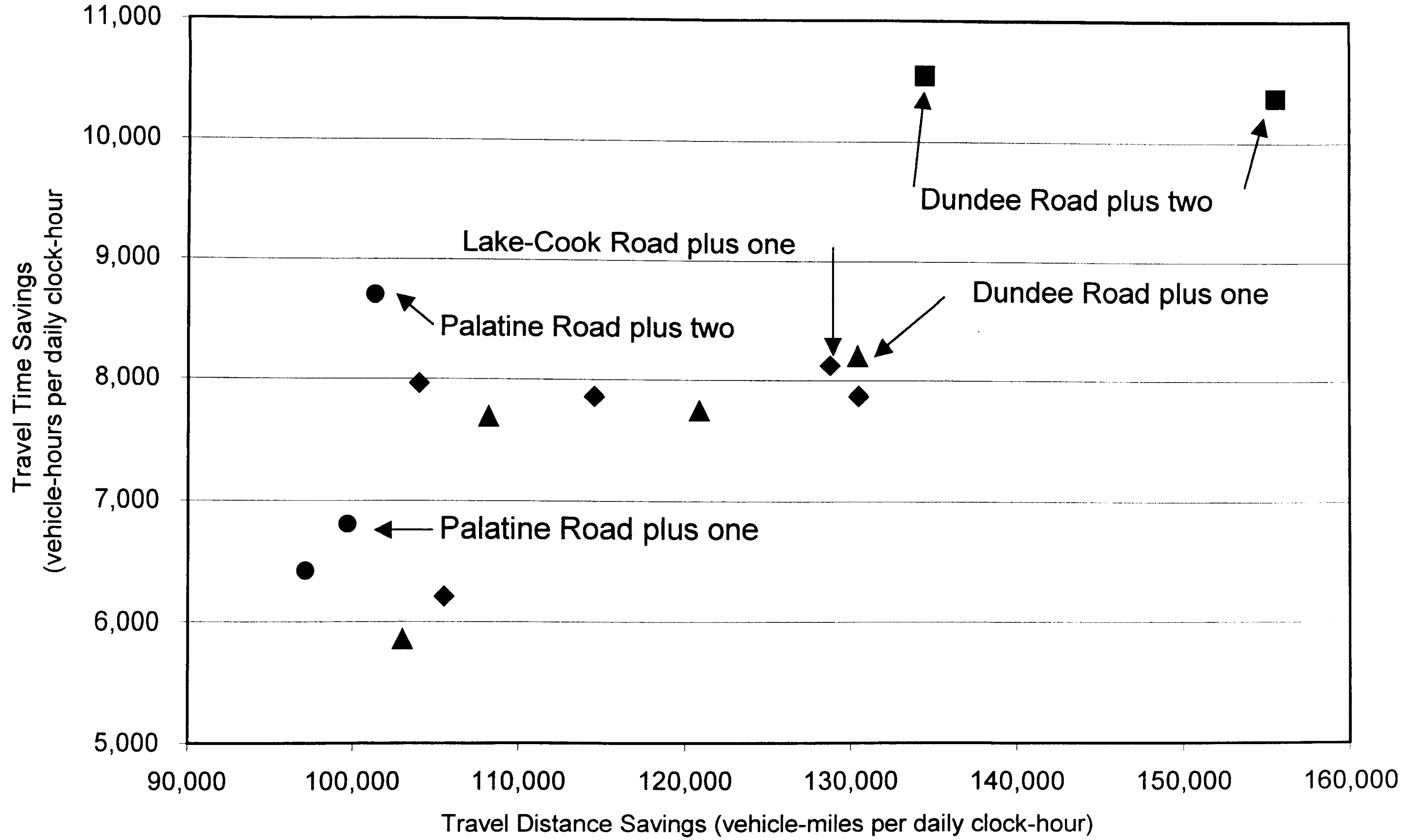


Figure 7. Travel Time Savings from Flood Protection at Milepost N Relative to the 5-Year Flood Event
(6 - 9 am period in 2020)

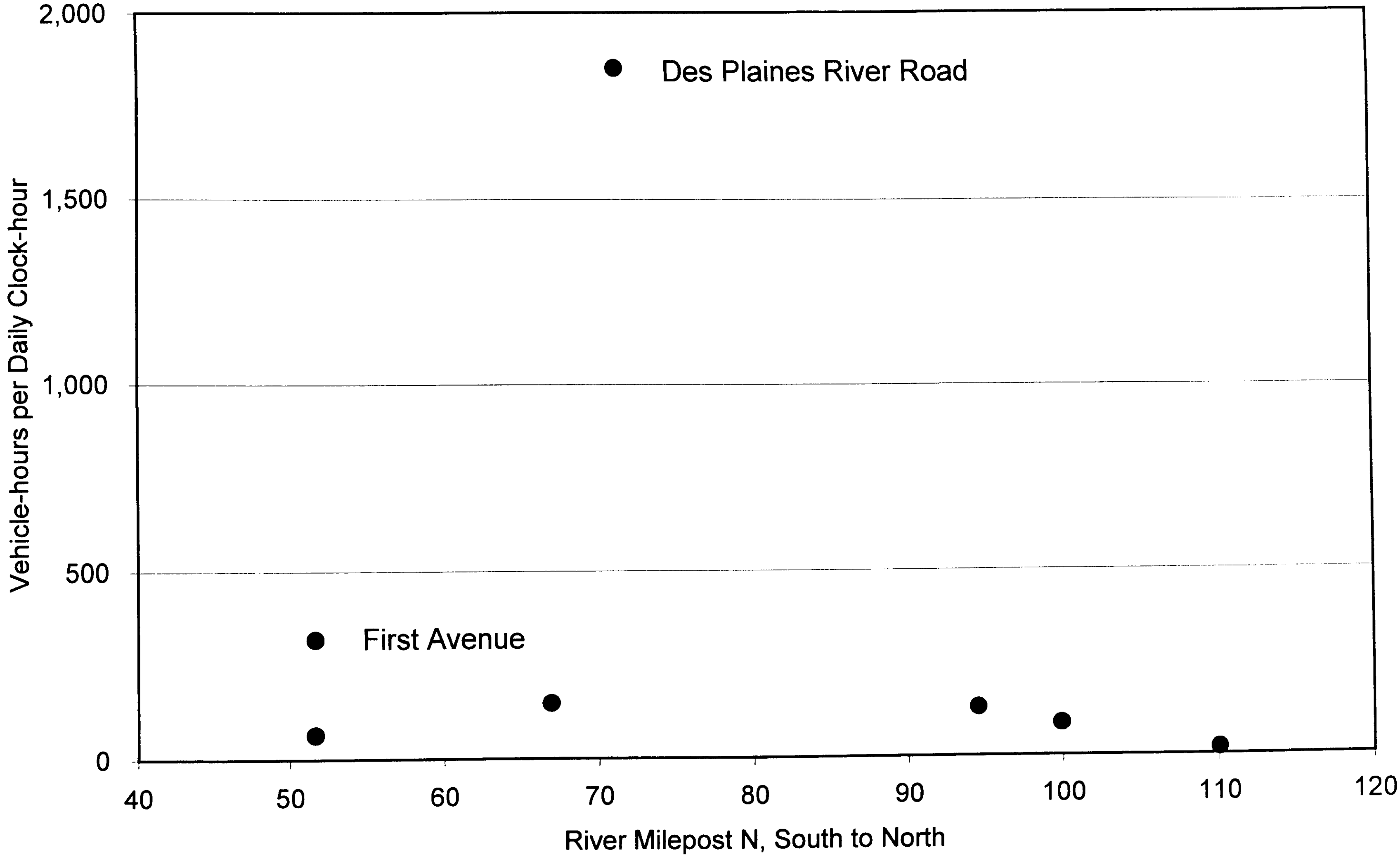


Figure 8. Travel Distance Savings from Flood Protection at Milepost N Relative to the 5-Year Flood Event

(6 - 9 am period in 2020)

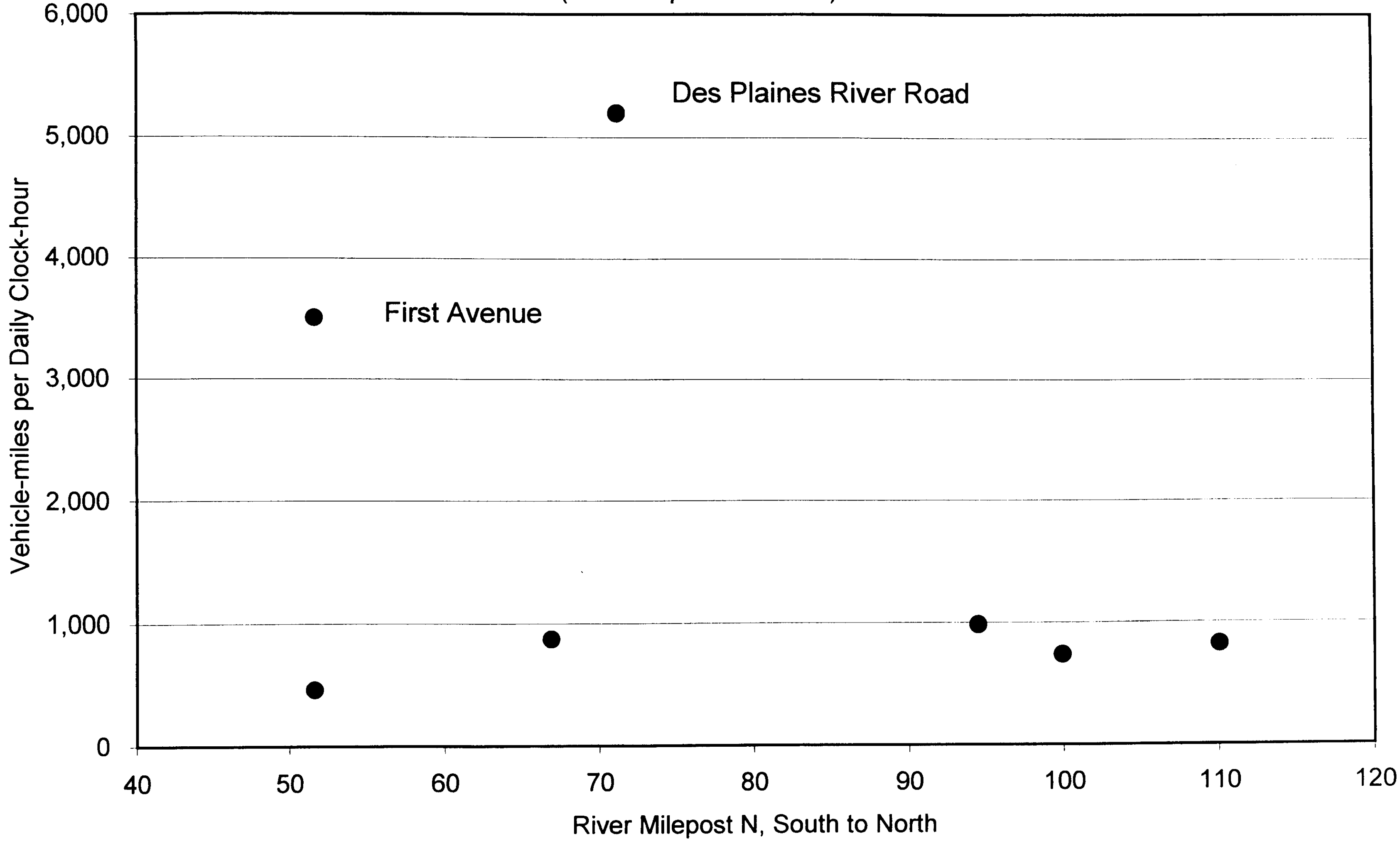


Figure 9. Travel Time vs. Distance Savings from Flood Protection at Each River Crossing for the 5-Year Flood Event
(6 - 9 am period in 2020)

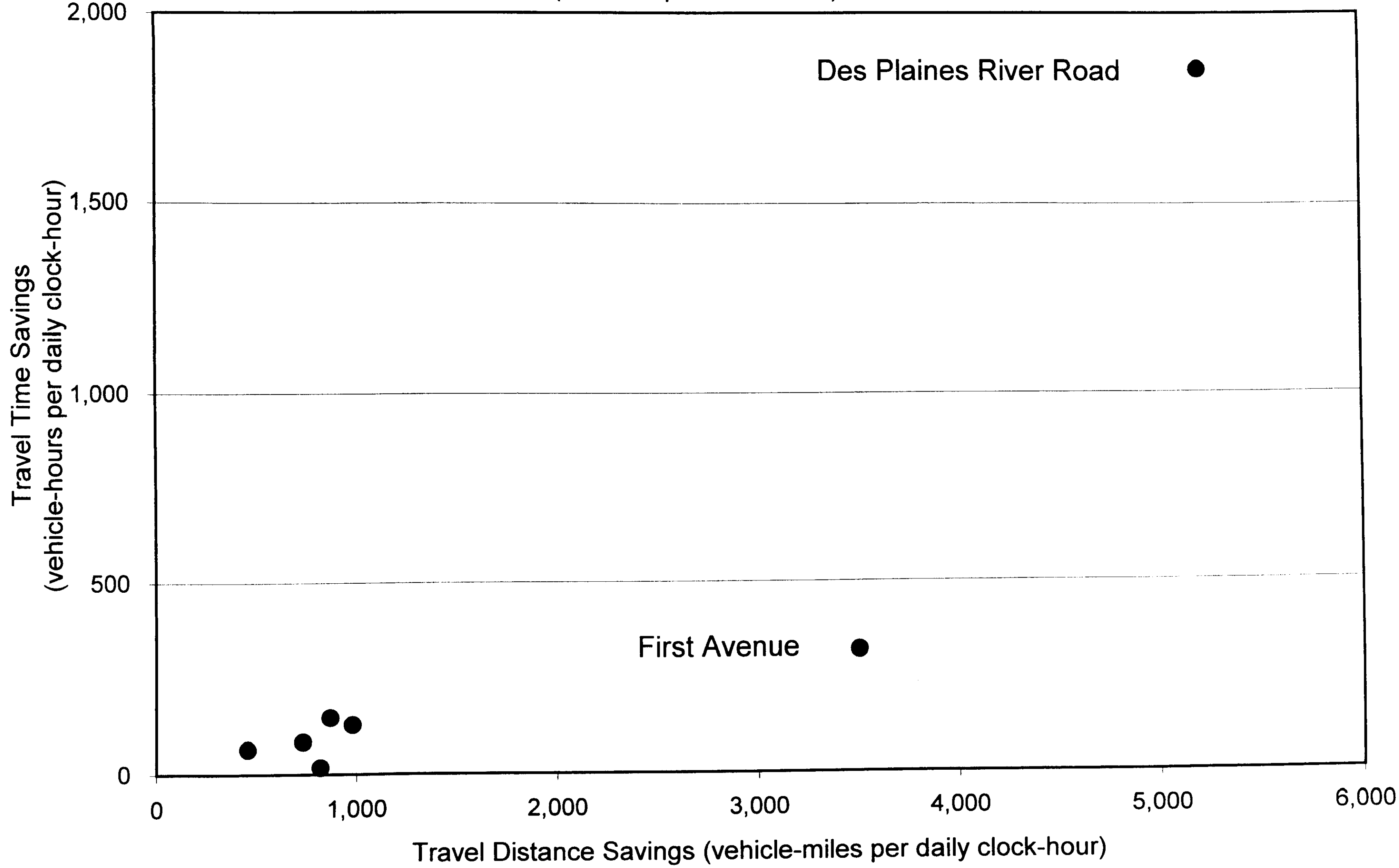
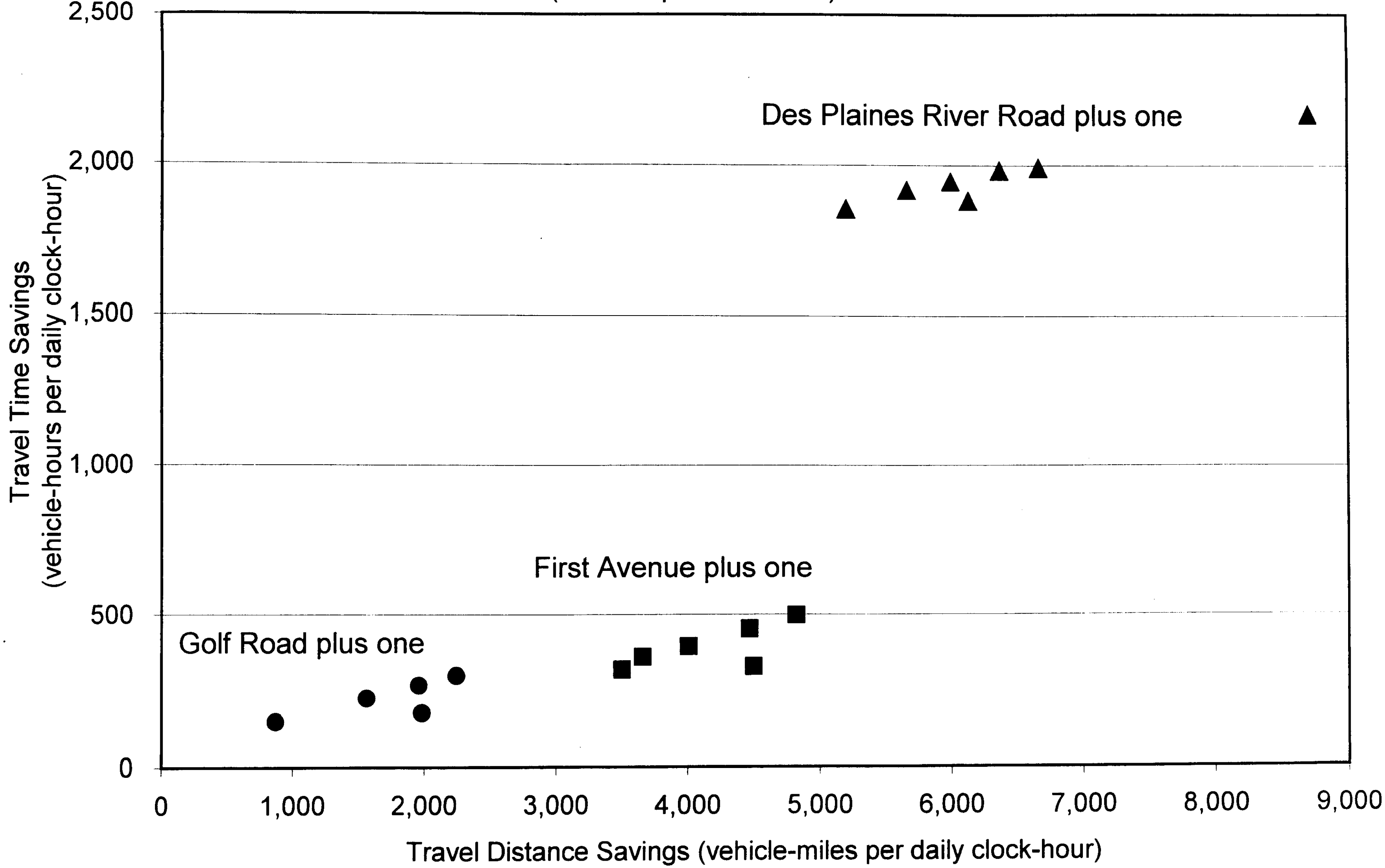


Figure 10. Travel Time vs. Distance Savings from Flood Protection for Combinations of Two River Crossings for the 5-Year Flood Event
(6 - 9 am period in 2020)



Appendix A-1

Formulation of the Traffic Assignment Problem

The Traffic Assignment Problem with fixed demand is defined as follows:

$$\min_{\mathbf{h}} z(\mathbf{h}) = \sum_a \int_0^{f_a} t_a(x)dx$$

$$\text{s.t.} \sum_{r \in R_{pq}} h_{pqr} = T_{pq}, \text{ for all } pq$$

$$h_{pqr} \geq 0, \quad r \in R_{pq}, \text{ for all } pq$$

where $f_a \equiv \sum_{pq} \sum_{r \in R_{pq}} h_r \delta^a_{pqr}$ for all a

$t_a(f_a)$ = travel time on link a at flow f_a

T_{pq} = flow of vehicles per day from origin zone p to destination zone q

h_{pqr} = flow of vehicles per day on route r, $r \in R_{pq}$, the set of routes from p to q

$\delta^a_{pqr} = 1$, if link a belongs to route r, $r \in R_{pq}$; 0, otherwise

The Gap at iteration k may be defined as:

$$\text{Gap}(k) = \sum_a t_a(f_a(k)) \cdot (y_a(k) - f_a(k)) \leq 0$$

where $y_a(k)$ is the vehicle flow on link a at iteration k given by an all-or-nothing assignment based on link travel times, $(t_a(f_a(k)))$.

Using the Gap, a Lower Bound (LB) on the value of the Objective Function $z(\mathbf{h})$ is defined as:

$$\text{LB}(k) = z(\mathbf{h}(k)) + \text{Gap}(k) = \sum_a \int_0^{f_a(k)} t_a(x)dx + \sum_a t_a(f_a(k)) \cdot (y_a(k) - f_a(k))$$

The Best Lower Bound (BLB) is then defined as: $\text{BLB} = \max_k [LB(k)]$, and

Relative Gap (k) = $\dfrac{\text{- Gap}(k)}{|\text{BLB}|} \geq 0$, where $|\text{BLB}|$ is the absolute value of the Best Lower Bound.

In this study the EMME/2 transportation planning software system was used to solve the Traffic Assignment Problem to a Relative Gap of 0.001.